THE _THREAT_ _RELATED_ _ATTRITION_ (THREAT) SYSTEM
CASUALTY ESTIMATION FACILITY MODEL

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The U. S. Air Force Human Systems Division, Operational Analysis Systems Division (HSD/YAO) and its contractor, BDM International, Inc., are developing a series of computer simulation models to estimate wartime personnel attrition on airbases. Casualty estimation in structures subjected to the effects of conventional munitions is a key part of this effort. This paper presents the methodology developed to estimate such casualties, and compares model results to historical and recent Gulf War events. While primarily focused on the effects of munitions against personnel in facilities, the underlying approach is felt applicable to a wide variety of problems in which an estimation of the effects of explosives against personnel is required.

A.   INTRODUCTION

Casualty attrition rates are used by numerous Air Staff offices to satisfy a variety of planning and programming requirements, including identifying medical manpower and material needs, planning for facilities and equipment, and identifying wartime personnel replacement needs. Because casualty estimates are essential to such wartime planning activities, the Air Force Human Systems Division (HSD/YAO) has undertaken a program to develop a consistent, auditable, and enduring modeling system to perform casualty estimation analysis. Acting as the HSD's prime contractor, BDM International is developing the THREAT (Threat Related Attrition) modeling system. The THREAT system is designed to respond to evolving worldwide threats, improvements in airbase facilities and protection systems, and developments in enemy weapon systems, to provide relevant and up-to-date attrition rate estimates.

The THREAT system is comprised of a number of integrated computer simulation models. At the most fundamental level are the _facility_ models, which predict casualties resulting from specific weapons delivered against individual structures. Results from the facility models are then used by higher level models to predict casualties for individual airbases and military theaters of operation.

Because the facility models represent the foundation of the THREAT system, their ability to accurately predict the numbers and types of casualties is key to the overall success of the system. This paper summarizes the methodology developed to accomplish facility modeling for the THREAT system and provides comparisons of model estimates to historical and recent Gulf War events.

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B. BACKGROUND

Airbase casualties are generally expected to be the result of air-delivered munitions against personnel in structures. In the past (Ref. 1), analysis of airbase attrition relied heavily on the application of casualty trends observed in the battlefield. Review of the literature shows that the nature and extent of casualties in structures is very much different than those which occur on the battlefield. In general, battlefield casualties are caused primarily by direct weapons effects such as overpressure and fragmentation. On the other hand, casualties in structures are due largely to secondary weapon effects, such as flying and falling debris, and structural collapse. The ratio of fatal to nonfatal casualties in structures is also different from that on the battlefield. The THREAT facility models attempt to account for these differences by pursuing a detailed examination of the forces acting on a structure, the response of the structure to the forces, assessment of interior hazards, and determination of casualties based on the severity of these hazards.

Weapon effects models developed in the past typically have not combined all of these factors. Methods, procedures, and data have been assembled to assess damage to buildings from conventional munitions (Ref. 2-5), however, these often lack the critical links between weapon effects and personnel survivability. A primary objective of this effort was to integrate the information necessary to estimate casualties in structures into a single computer simulation model.

Initial development of the facility models focused on providing a capability to examine the effects of specific bombs versus particular structure types. The first structure types examined include unprotected and select protected facilities. Munition types include conventional general purpose bombs of varying sizes. Development of these models provide a proof-of-concept for the modeling system as a whole and serve as a baseline for future system upgrades.

C. MODEL DESCRIPTION

The facility models are designed to provide detailed assessments of the effects of general purpose bombs delivered against airbase facilities. Currently modeled structural classes include unprotected, NATO semihardened (above ground and buried), and survivable collective protection shelters (SCPS). The response of each structure is very much dependent on its construction. For this reason, each class of structure is modeled separately. A complete treatment of each class is beyond the scope of this paper. To illustrate the methodology in general, the unprotected facility model will be discussed.

Each model has five principal components, including facility and weapon event description, weapon effects, structural response, interior environment assessment, and casualty estimation. A summarized description of each segment is provided below.

1. Facility and Weapon Event Description

To allow assessment of a variety of unprotected structures, structure data files were developed to represent typical unprotected facilities on an airbase. These included unreinforced masonry, reinforced concrete frame, steel frame, and wood frame. The structure data files contain a simplified representation of each structure. Information stored in the data files includes the size of the building; the number of stories; the number of rooms per story; the number and types of walls, floors, ceilings, columns, beams, and windows; and the location, orientation, and interdependencies of the components. For unprotected structures, the data files also contain rules to predict progressive structural collapse following assessment of the primary weapon effects.

The model user initiates execution of the program by selecting the facility type to be analyzed. The user then specifies the weapon, detonation location, and soil type. Weapon choices include 100-, 250-, 500-, 1000-, and 2000-pound general purpose bombs. Soil types include dry loose sand, wet loose sand, dry dense sand, wet dense sand, moist clayey sand, wet silt clay, wet sandy clay, and saturated sandy clay. Direct hits may be analyzed by specifying weapon detonation locations within the structure. The model does not specifically address weapon fuzing, penetration, ricochet, or trajectory (it is left to the analyst to specify realistic weapon detonation locations). Initial populations of each room are also specified by the user.

2.   Weapons Effects

The detonation of a weapon, such as a general purpose bomb, produces several effects that may pose a hazard to structures and/or personnel. General purpose bombs are comprised of essentially three components: an outer steel casing, an inner high explosive charge (such as TNT), and a fuze. Fuzes may be set to trigger either above ground, on contact, or at some prescribed time after contact. In general, contact fuzed weapons are used for attacking soft, above-ground targets, and delay fuzed weapons are used for attacking buried or hardened targets.

A contact fuzed weapon detonating on the ground surface will generate shock waves in the air. This is termed airblast and is considered the primary threat to above-ground structures[1]. Airblast pressures in the freefield are termed incident pressures and are typified by an instantaneous rise in pressure followed by an exponential decay. Integration of the area under the pressure-time history is referred to as the blast impulse. Peak incident pressure and impulse are a function of the weapon charge weight and range from the explosion, and are defined in the literature (Ref. 3). The pressure-time history is commonly simplified as a triangular pulse having an instantaneous rise and linear decay. This approximation is represented in the model as follows:

$$P_i(t) = P_0\left(\frac{t - t_0}{t_0}\right) \quad \text{for } t \le t_0 \tag{1}$$
$$= 0 \quad \text{for } t > t_0$$

where:

$P_i(t)$ = positive incident pressure as a function of time
t = reference time
P_0 = peak positive incident pressure (psi)
t_0 = positive phase duration (msec) = $2i_s/P_0$
i_s = positive phase impulse (psi-msec)

As the shock wave strikes an object, the interface pressure acting on the object intensifies based on the angle of incidence between the object and the pressure wave, and the magnitude of the pressure wave. A reflection factor $C_{r\alpha}$ is found from empirically derived relationships available in the literature (Ref. 3). To calculate reflected pressure and impulse, the model determines the distance and reflection angle between the weapon and structural components having line-of-sight to the detonation. The magnitude of the reflected pressure and impulse acting on these components is stored and used later for structural response calculations.

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[1] While fragment loading is also a concern, airblast is dominant and its effects are assumed to be the primary indicator of damage. Assumption consistent with the literature (Ref. 2).

Delay fuzed weapons detonating below the ground surface will generate cratering and groundshock. Both these phenomena are strongly dependent on the soil type in which the event takes place. Crater dimensions are calculated in the model based on standard relationships found in the literature (Ref. 3). Groundshock, while a significant threat to buried structures, is not calculated as a threat to above-ground, unprotected structures[2].

Weapons which penetrate and detonate inside a hardened structure generate extreme levels of airblast overpressure due to confinement of the blast by the structure itself. Such confined overpressures are not calculated for detonations inside unprotected structures. The relatively light walls of unprotected structures are assumed not to provide the blast containment necessary to develop such pressures. While it may be true that unprotected structures confine the blast to some degree, analysis of this point was beyond the scope of the model at this time.

3.   Structural Response

In general, the response of a structure to airblast forces will be a function of either the pressure, impulse, or a combination of both. Identification of the dominant response mode can be made by examining the duration of the blast load T and the natural period of the structure T_n (Ref. 2):

$$\frac{T}{T_n} \leq 0.3, \qquad \text{response impulse dependent only} \qquad (2)$$

$$0.3 < \frac{T}{T_n} < 50, \qquad \text{response pressure and impulse dependent} \qquad (3)$$

$$\frac{T}{T_n} \geq 50, \qquad \text{response pressure dependent only} \qquad (4)$$

The relatively short duration loads from general purpose bombs of the size included in this study produce duration-to-natural period ratios of less than 0.3 for most structural components (Ref. 2). Exceptions include brittle components such as windows.

The response of the structure as a whole is calculated by assessing the response of individual components. The capacity of components to withstand impulse forces was obtained from the literature (Ref. 2). Data are stored on the reflected impulse required to cause slight, moderate, and total damage for each component. Component types currently available in the model include unreinforced masonry walls (4 to 12 inches); reinforced masonry walls (6 to 12 inches); reinforced concrete walls (4 to 12 inches); light stud/metal walls; light metal, wood, and concrete floor/roof elements; and heavy timber, concrete, and steel beams and columns. Windows are pressure sensitive and the reflected pressure required to cause breakage is stored.

The model initiates assessment of the facility by first determining those components having line-of-sight to the weapon. The reflected impulse and pressure are calculated as described above. Based on the impinging reflected impulse, components are classified as having either total, moderate, slight, or no damage. Should a wall, floor, or ceiling element suffer total damage, the model "opens" the adjoining room to subsequent blast effects. In this way the blast is tracked as it propagates through the facility.

Blast can be attenuated to a significant degree as it propagates through a structure. Review of the literature (Ref. 6) on the effects of 250 kg general purpose bombs against unreinforced masonry dwellings indicates the

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[2] Assumption consistent with the literature (Ref. 2)

average radius of full demolition for near-miss events was significantly greater than that for direct hits. The reason is that for direct hits, blast must propagate through more obstructions (walls, ceilings, etc.) than for near misses (where blast may propagate unobstructed over large distances). This attenuation of blast by building components is represented in the facility models.

For buried detonations, damage to unprotected structures is based on the dimensions of the crater with respect to the facility. First floor components within the crater itself are assumed to be totally destroyed. Component damage then decreases with increasing distance. For shallow buried detonations which generate both airblast and cratering, the effects of each are assessed. Damage is determined as the greater of the two effects.

Following assessment of the primary weapon effects, the model assesses progressive structural collapse. As stated earlier, collapse rules are stored in the structure data file. The rules define loadbearing dependencies between components. Should a loadbearing wall on the second story have the first story wall below it destroyed by blast, the second story wall would be noted as unstable, and would be assessed to be collapsed. Currently, the model does not assess collapse from the dynamic loading of upper-level debris falling on lower levels.

4.   Interior Environment

After analyzing the structure's response to the weapon, the model assess the relative severity of hazards to personnel in each room. Hazard environments assessed include overpressure, velocity (floor motion) primary fragments (bomb splinters), secondary projectiles (flying debris) and collapse (falling debris). Hazards are rated from each cause as either severe, moderate, light, or none. Each cause is described below.

Fast rising overpressure can injure personnel as the overpressure compression wave propagates through the body and reflects at internal air-tissue interfaces, such as the ears and lungs. Common injuries include ruptured ear drums and lung lesions. The model records the peak incident pressure and duration in each room as the blast propagates through the facility. These values are then compared to overpressure injury relationships described in the next section which relate a person's probability of sustaining a fatal, serious, or slight injury to the magnitude and duration of the overpressure. Based on this assessment, overpressure hazard is rated.

Personnel may be injured from being knocked off their feet and/or otherwise displaced as the floor heaves in response to the blast. This phenomena was designated velocity hazard. Velocity hazard is assessed by noting the state of a room's floor damage. It was assumed that increasing floor damage corresponded to increasing velocity hazard. Based on the final floor damage state, velocity hazard is rated.

Primary fragments are pieces of the weapon casing flying away from the detonation at extremely high velocities (5000 to 7000 fps). Primary fragments are the most significant injury mechanism for weapons detonating in the open against unprotected personnel. However, in structures, the literature indicates that even light partition walls provide surprisingly effective protection (Ref. 9). The severity of the primary fragment hazard is rated in the model based on the distance and number of intervening walls between the weapon and personnel at risk.

Secondary projectiles are created when a wall is breached or spalled by blast, causing numerous pieces of concrete, masonry, and other building materials to fly through the air. The severity of the secondary projectile hazard was rated based on the damage sustained by the walls of a room. It was assumed that increasing wall damage corresponded to increasing secondary projectile hazard. Based on the final damage state of all walls associated with a room, the secondary projectile hazard is rated.

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Personnel may also be injured from falling pieces of debris. This phenomena was designated collapse hazard. Collapse hazard is assessed by noting the state of a room's ceiling damage. It was assumed that increasing ceiling damage corresponded to increasing collapse hazard. Based on the final ceiling damage state, collapse hazard is rated.

5.   Casualty Estimation

Following assessment of the interior hazards described above, the model estimates the resultant casualties in the structure. To accomplish this, links had to be established between the hazards and the probabilities of personnel sustaining fatal, serious, and slight injuries. Establishing these links was perhaps the most difficult aspect of the study, given the natural variability in expected personnel location and posture, the complexities of estimating human response to trauma, and the inability to precisely define the environment to which personnel would be subjected. However, the literature does provide information from laboratory studies and historical events. Combining these sources allowed provisional relationships to be defined. Research is ongoing to better define these relationships.

Overpressure casualties are estimated based on the magnitude and duration of the incident pressure in a room. The literature (Ref. 10-12) provides information from animal studies extrapolated to estimate human response. The casualty relationships derived from this information was implemented into the models.

Casualties from velocity, primary fragments, secondary projectiles, and collapse were developed from historical events. The literature provided information from the London Blitz which identified actual numbers and causes of casualties at various ranges and levels of structural damage from the listed hazards. This information was used along with engineering judgment to establish the casualty frequencies for the above causes based on their severity.

The method for determining casualties in a room is as follows. Given that the model has determined the probability of personnel incurring a fatal injury from hazard i (denoted $p_{k(i)}$), a fatal or serious injury from hazard i (denoted ($p_{k+s(i)}$), and fatal or serious or slight injury from hazard i (denoted ($p_{k+s+sl(i)}$), and all n hazards have been assessed, the overall probability of incurring a fatal injury P_k in a room is calculated as:

$$P_k = 1 - \prod_{i=1}^{n} [1-p_{k(i)}] \tag{5}$$

the overall probability of incurring a fatal or serious injury P_{k+s} in a room is:

$$P_{k+s} = 1 - \prod_{i=1}^{n} [1-p_{k+s(i)}] \tag{6}$$

and the overall probability of incurring a fatal or serious or slight injury P_{k+s+sl} in a room is:

$$P_{k+s+sl} = 1 - \prod_{i=1}^{n} [1-p_{k+s+sl(i)}] \tag{7}$$

The numbers of fatal N_f, serious N_s, and slight N_{sl} in a room is then found based on the above probabilities and the initial population of the room N_{init} as:

$$N_f = N_{init} (P_k) \tag{8}$$

$$N_s = N_{init} [(P_{k+s}) - P_k] \tag{9}$$

$$N_{sl} = N_{init} [(P_{k+s+sl}) - (P_{k+s})] \tag{10}$$

Fatal, serious, and slight casualties are then summed over all rooms to obtain total estimated casualties in the facility.

D.   MODEL VALIDATION

To validate the performance of the model, comparisons were made between model results and historical data. To accomplish this, a typical block of row houses of the size and construction type prevalent in London during World War II was simulated. Two points of comparison were pursued: (1) comparison of modeled to historical results of the degree of structural damage caused by general purpose bombs, and (2) comparison of modeled to historical results of the frequency of fatal, serious, and slight casualties as a function of range from the weapon.

To compare the damage caused by general purpose bombs, information was available in the literature describing the damage suffered by London rowhouses due to German bombs. Using the simulated block of rowhouses, bombs were modeled at over 500 locations in and around the houses. Depth-of-burst estimates were made based on reported crater dimensions from the historical data. Results from all modeled events were tabulated. Comparisons between modeled and historical damage and casualties were favorable, and thus supported use of the models to represent weapons and facility types for which historical data is not available.

Comparisons are now being pursued between modeled and actual causes of casualties at various ranges. Calibration of the models using such historical data provides the best and most realistic estimate of casualties expected from conventional munitions delivered against personnel in unprotected structures.

E.   GULF WAR EVENT COMPARISON

The reason for developing the model described above is to provide military planners the capability of estimating casualties in modern structures subjected to modern weapons. The THREAT models were used in a program initiated before the Gulf War to estimate expected numbers of noncombatant casualties in Baghdad, Iraq. Post war surveys have indicated that the THREAT System estimates were quite accurate. Additionally, an event occurred during the war for which the accuracy of the facility model could be checked directly. On February 25, 1991, an Iraqi Scud missile struck an aircraft hangar being used to house U. S. personnel supporting Desert Storm operations. Of the roughly 150 troops in the hangar, 28 were killed and 100 injured[3]. In the aftermath of this event, the facility model described above was exercised to investigate the correlation between the model and the actual event. Because of limited information regarding the exact weapon type, detonation location, structure type, and distribution of personnel in the facility, certain assumptions were made. These assumptions were as follows:

  • Of the Scud missiles in the Iraqi inventory, the most probable one used against the U. S. troops was the *Al Hussein*. The *Al Hussein*[4] is a derivative of the Soviet *Scud-B* missile, modified to achieve greater range through additional solid propellant and reduced warhead weight. The warhead is a conventional high explosive blast/fragment type with a total weight of

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[3] Figures reported by Cable News Network (CNN), February 26, 1991.
[4] Source: Janes Strategic Weapons Systems, 1989.

about 1100 lbs, estimated charge weight of 550 lbs. Characteristics of the warhead were deemed similar to a general purpose bomb of similar weight.

- The structure used to house the troops was a steel framed, metal sided aircraft hangar. The hangar structure currently available in the facility model was used to represent this structure. The modeled hangar has dimensions of 200 by 150 by 30 feet. The shelter is open inside and offers no protection from interior walls.
- Troops were evenly distributed throughout the facility. Protective gear was not in use, and the vulnerability of personnel to weapon effects was essentially similar to the civilian population studied above.
- The Scud missile struck roughly in the center on the hangar and detonated on contact with the ground.

Based on these assumptions, the modeled results were as follows (modeled serious and slight injuries were summed to obtain total injuries):

EVENT	KILLED	INJURED
Actual	28	100
Modeled	20	79

It should be noted that the THREAT models account for casualties resulting from direct and secondary weapons effects (overpressure, fragmentation, falling debris, etc.) but do not account for subsequent casualties due to fire. This may account for the model's underprediction. However, given the inherent uncertainties in any such analysis, the results were viewed as excellent.

F.   CONCLUSIONS
The existing facility-level models provide a useful tool for estimating personnel casualties in structures. New weapon and facility types are being added to increase the scope of the models' analysis capabilities. A great deal of work still needs to be completed to fine tune the models, especially in the area of human vulnerability. This is an ongoing research effort, and upgrades to the models are expected to be evolutionary in nature. Continued model development should offer significant opportunities to assess the effectiveness of evolving weapon and protection systems, and allow for effective post attack recovery operation planning. The underlying approach, which relies on a fundamental assessment of weapon effects, structural response, and human vulnerability, is felt applicable to a wide variety of problems in which an estimation of the effects of explosives against personnel is required.

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